Non-thermal magnetospheric process in AGN

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General remarks

Formation of jets is reasonably well understood. But!

- what is the dissipation mechanism?
- origin of plasma source in the magnetosphere?
  (external pp, spark gap, etc)
This talk

- Plasma injection in BH magnetosphere and consequences for high-energy emission
- Preliminary results of 3D FF simulations of loop accretion
BZ mechanism works

Size of the Milky Way (100,000 ly)

LOFAR 0.05 GHz

100 arcsec
(30,000 ly)

VLA 1.5 GHz

0.001 arcsec
(0.3 ly)

VLBA 43 GHz

0.00001 arcsec
(0.003 ly)

EHT 230 GHz

M87 - collimation profile

From Nakamura+ 13

\( r_j \propto z^{0.56} \)

Collimation break associated with the HST-1 knot
Stratified flow in M87

Mertens + 16
M87

Strong flares observed in 2005, 2008, 2010

$L_j \approx 10^{43} \text{ erg s}^{-1}, \quad L_\gamma \approx 10^{41} \text{ erg s}^{-1}$

Variability time $\approx 1 \text{ day} \sim r_s$

TeV emission from inner region or a remote, small region?
Multi-flow

Two flow MHD model
(Garcia + '09; Nakamura + Asada '13)

Jet-sheath structure in GRMHD simulations (Moscibrodzka + '13)

disk winds (McKinney '06; Globus + AL '16)

- Slow components from sheath flow?
- Relativistic components + HE emission (particularly variable TeV emission) from inner jet?
Emission from sheath flow

Proton temp. in accretion flow is virial: \( T_p \sim 0.1 m_p c^2 \)

and \( T_e / T_p < 1 \Rightarrow \gamma_{e,th} < 10^2 \).

- Radio emission at small radii arises from sheath.
- VHE emission from sheath requires effective electron acceleration there!

Variable TeV emission from inner jet? Sheath?
Requires rapid dissipation of B field!!
I. Plasma production and activation of BH outflows
Plasma injection in the magnetosphere

• plasma source between inner and outer Alfvén surfaces
• escape time $\approx$ few $r_g/c$

$\gamma\gamma \rightarrow e^\pm$ in AGNs
$\nu\nu \rightarrow e^\pm$ in GRBs

mass loading?

Globus+AL 2014

Barkov + ‘08
How to produce the required charge density?

- Protons from RIAF?
- Protons from n decay?
- $e^\pm$ from $\gamma\gamma$ annihilation?
- Other source?

- Protons have to cross magnetic field lines. Diffusion length over accretion time extremely small.

- Instabilities or field reversals. But intermittent spark gaps may still form.
Direct pair injection by $\gamma \gamma \rightarrow e^\pm$

Requires emission of MeV photons:
- Low accretion rates: from hot accretion flow
- High accretion rate: from corona?

Example: M87
Direct pair injection

- Low accretion rates (RIAF): AC may be hot enough to produce gamma-rays above threshold (Levinson + Rieger 11, Hirotani + 16)

Conditions for gap formation (From Hirotani+ 16)
Criteria for gap formation: non-RIAF

- Intermediate accretion rates: Disk is cold, but corona may scatter photons to MeV energies.

Condition for gap formation

\[
\frac{L_\gamma}{L_{Edd}} < 10^{-3} \left( \frac{B}{10^8 G} \right)^{1/2} \left( \frac{R_\gamma}{30 r_g} \right)^2
\]

Stellar BH: \( B \approx 10^8 \, G \)

AGNs: \( B \approx 10^4 \, G \)

Model SED of a 5 M_\odot BH at different states (from Chakrabarti + 95)
Activation of a spark gaps

- Activated when $n < n_{GJ}$.
  Expected in M87 when accretion rate $< 10^{-4}$ Edd.
- Must be intermittent (Segev+AL 17).
- Particle acceleration to VHE by potential drop.

AL 00; Neronov + '07, AL + Rieger '11, Broderick + 15; Hirotani+ 16, 17
GRPIC Simulations
With Benoit Cerutti and his Zeltron code

- Fully GR (in Kerr geometry)
- Inverse Compton and pair production are treated using Monte-Carlo approach.
- Curvature emission + feedback included
- Currently 1D local gaps
- Goal: 2D global simulations
1D model

AL + Cerutti 18

Global structure

- Solves GRPIC equations along a particular field line
- Magnetospheric current is a given parameter

[Diagram showing global structure with stagnation surface, null surface, and electric flux in simulation box]
Example

\[ \tau_0 = \sigma_T n_{ph} r_g \sim \text{Pair-production opacity across gap} \]

\[ \tau_0 = 10 \]
Luminosity during quiescent state

Pair multiplicity

\[ J_0 = 1, \, ct/r_g = 21.11 \]

\[ \langle \kappa \rangle \]

\[ \langle \gamma \rangle \]

\[ \langle \epsilon \rangle \]

\[ \tau_0 \]

Photon energy

\[ \langle \epsilon \rangle \]

\[ \tau_0 \]

\[ \frac{L}{L_{BZ}} \]

\[ \frac{L_{IC}}{L_{curv}} + \frac{L_{kin}}{L_{IC}} \]
\( \tau_0 = 0.01 \)
M87- radio emission?

\[ r_s \approx 1.8 \times 10^{15} \text{ cm} \approx 1 \text{ day} \text{, } L_{EHT} \approx 3 \times 10^{40} \text{ erg/s} \]

Density of emitting electrons:

\[ n_e = \frac{L_{EHT}}{P_{syn} V} \sim 10^5 (R/r_s)^{-3} B^{-1} \text{ cm}^{-3} \]

GJ density:

\[ n_{GJ} \approx 10^{-7} (2\Omega/\omega_H)B \text{ cm}^{-3} \]

So, not from a gap! Most likely from sheath

If from jet (baryonic matter):

\[ L_j > 10^{43} \left(\frac{n_p}{n_e}\right) \Gamma^2 B^{-1} (R/r_s)^{-1} \text{ erg/s} \]
II. Dissipation of magnetized jets

Large scale (ordered) B fields:
efficient jet production \((\text{MAD, MCAF, etc.})\)
but stable! dissipation requires rapid growth of instabilities

Small scale B field:
quasi-striped configuration \((\text{good for dissipation and loading})\)
Smaller efficiency
Dissipation of ordered field
Small angle reconnection via CD  kink inst.

3D simulations of a magnetic jet propagating in a star

kink instability requires strong collimation. Develops fastest in a collimation nozzle.

But even then, saturates at equipartition.
M87 – parabolic jet

From Nakamura+ 13

\[ r_j \propto z^{0.56} \]

Is this jet stable or not?
quasi-striped jet

Reconnection of non-symmetric component

Dissipation on scales:
\[ r_{\text{diss}} \sim \frac{\lambda \Gamma_0^2 \beta_{\text{rec}}^{-1}}{r_g} \]

Difficult to account for extreme flares (but see next)

Romanova + Lovelace 92
AL + Van Putten 97
Drenkhahn + Spruit ‘02
AL+Globus ‘16
Accretion of flux loops

Spruit, uzdenski, goodman

Reconnection can lead to electron acceleration in the jet + sheath. Potential site of VHE emission.

Van Putten + AL ’03
Kadowaki, de Gouveia Dal Pino + ‘15

2D Simulations by Parfrey + ‘15
3D GRFF simulations of loop accretion

Jens Mahlmann (with M. Aloy and AL)

Preliminary results
Conclusions

- Spark gaps may form if survival time of coherent magnetic domains exceeds a few dynamical times. May be the production sites of variable VHE emission.

- Gaps are inherently intermittent.

- Pair discharges by rapid plasma oscillations, emitting TeV photons with $L_{\text{TeV}}/L_{\text{BZ}} \sim 10^{-5}$.

- Strong TeV flares can be produced if gap is restored.

- Loop B accretion may produce favorable dissipation sites near the BH.